Overview of Model-Based Systems Engineering Efforts to Evolve the Airspace Research Roadmap

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NASA's Air Traffic Management-Exploration (ATM-X) UAM Airspace Subproject is conducting research that evolves UAM airspace towards a highly automated and operationally flexible system of the future. The complexity of UAM airspace evolution requires a plan to effectively organize, integrate, and communicate NASA's research and development. The planning tool, called the UAM airspace research roadmap, or just roadmap, is key to the execution of NASA's UAM airspace research over the next ten years. Implemented through Model-Based Systems Engineering (MBSE) methodology, the roadmap will help to prioritize and coordinate research efforts, and to integrate results that build towards NASA's research goals of evolving UAM airspace for integration of UAM operations into the National Airspace System (NAS). This paper presents an overview of on-going MBSE efforts to meet these overarching goals.

I. Introduction

Advanced Air Mobility (AAM) encompasses a range of innovative aviation technologies (small drones, electric aircraft, automated air traffic management, etc.) that are transforming aviation's role in everyday life, including the movement of goods and people. The concept of Urban Air Mobility (UAM) is composed of certain AAM concepts that provide commercial services to the public over densely populated cities and the urban periphery, including flying between local, regional, intra-regional, and urban locations using revolutionary new electric Vertical Takeoff and Landing (eVTOL) aircraft that are only just now becoming possible. The improvement of UAM envisages a future in which advanced technologies and new operational procedures enable practical, cost-effective air transport as an integrated mode of movement of people and goods in metropolitan areas.

To safely support these revolutionary vehicle operations at scale in the National Airspace System (NAS), NASA's Air Traffic Management-Exploration (ATM-X) UAM Airspace Subproject, or herein Subproject, is conducting research that evolves UAM airspace towards a highly automated and operationally flexible system of the future. The scope of NASA's research into the UAM airspace system is defined to encompass the airspace itself and the system of systems that comprise the UAM operations within. This is understood to include the conduct of UAM operations in relationship to other NAS operations, the supporting technologies and information exchanges, and the architecture of the associated systems and services.

The UAM Maturity Level (UML) scale (Ref. [1]) developed by NASA provides insight into UAM operational, technical, and regulatory progression in the NAS. The UML scale is a useful framework for understanding and evaluating the evolution of the NAS as it pertains to UAM. Ref. [2] further defines UML scale specifically for the airspace system from UML-1 to UML-4. Brief definitions are given here. First, UML-1 represents the (current) pre-

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operational phase, where only traditional vehicles (i.e., not eVTOL) are approved for operations in the NAS. Second, UML-2 represents initial commercial UAM eVTOL operations under existing regulations which utilize existing regulations, policy, and airspace structures. These operations are expected to take place in carefully chosen early adopter markets where operational challenges can be eased with non-regulatory accommodations where possible. Third, UML-3 represents the novel application of regulatory and airspace constructs (e.g., cooperative UAM corridors) and the supporting systems and services, designed to overcome the capacity constraints of UML-2. Lastly, UML-4 represents the integration of UAM operations with a greater diversity of NAS users, under more complex meteorological conditions, with the support of more complex safety-critical systems and digital exchanges, enabled by changes to the regulations with associated changes to policies and procedures.

The complexity of UAM airspace evolution through the UML scale requires a plan to effectively organize, integrate, and communicate NASA's research and development. The UAM airspace research roadmap (Ref. [2]), or herein roadmap, is a system engineering approach, implemented through Model-Based Systems Engineering (MBSE) methodology, to manage what is known, what is developed, and what is planned for in NASA's UAM airspace research & development lifecycle to meet the goal of *evolving the UAM airspace towards UML-4*.

This paper is organized in the following manner: Section 2 is the general MBSE background information. Section 3 describes the various MBSE's systems models in support of roadmap development lifecycle. Section 4 briefly discusses the planned MBSE activities within the Subproject in support of this roadmap.

II. MBSE Methodology

The International Council on Systems Engineering (INCOSE) vision (Ref. [3]) defines MBSE as "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. MBSE is part of a long-term trend toward model-centric approaches adopted by other engineering disciplines, including mechanical, electrical and software." Enabling MBSE as a standard practice requires several systems engineering standards, including modeling standards.

One of the modeling standards is the Systems Modeling Language (SysML). SysML is a general-purpose modeling language for systems engineering applications. The reader is directed to Ref. [4] for a thorough description of SysML. Partial elements of SysML related to this paper are summarized here. SysML includes nine diagrams, covering different aspects (e.g., structure, behavior, requirement, etc.) of the system of interest. System architecture (system decomposition and inter-connections among sub-systems) is an example of structural diagrams. Concept of operations (ConOps) are modeled through behavioral diagrams. Lastly, requirement diagrams give text-based requirements and their relationships not only to other requirements but also to design elements in support of requirement traceability. Other dependencies (e.g., allocation, refine, etc.) can also be specialized and used to display traceability among design elements.

III. Systems Models for Roadmap Development Lifecycle

To support the roadmap development lifecycle, four systems models are developed concurrently using the SysML standard. Each model focuses on different aspects of the UAM airspace system and has different owners responsible for the model's content. The four models are: (I) the Stakeholder Model, (II) the Airspace Roadmap Model, (III) the Airspace Services System Model, and (IV) the Communication, Navigation, and Surveillance (CNS) Model. Figures 1 and 2 present an overview of these models and their high-level dependencies, and their associated meta-model[4], respectively. It is important to note that all models along with their meta-model represent on-going efforts being developed and matured as the research within the Subproject progresses.

[4]meta-model represents abstraction syntax that describes the concepts, the relationships between the concepts, and a set of rules about how the concepts can be put together (Ref. [4]).

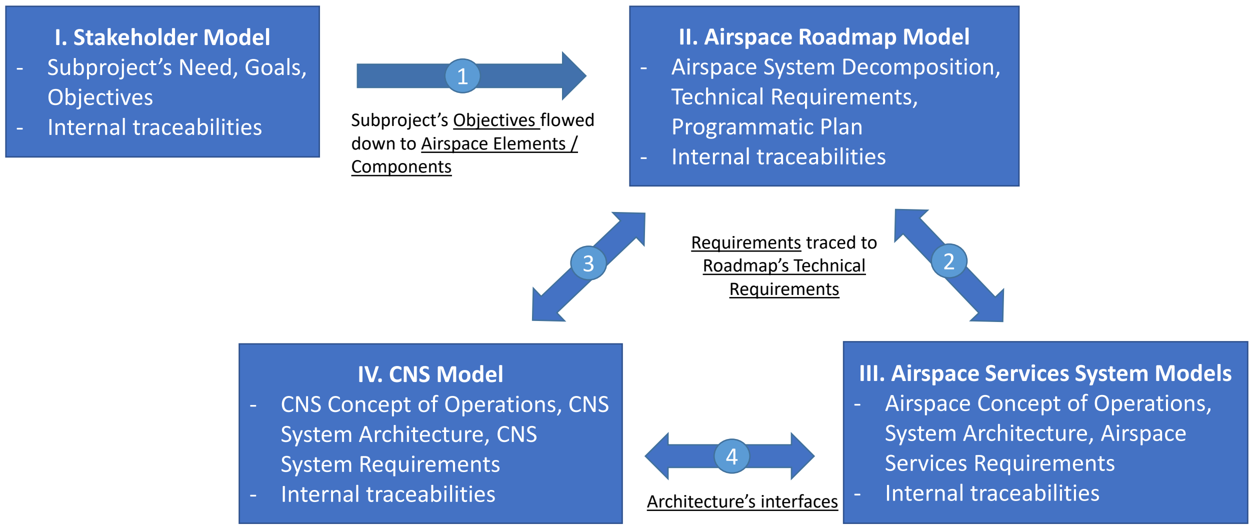

Fig. 1 Overview of systems models and their high-level dependencies.

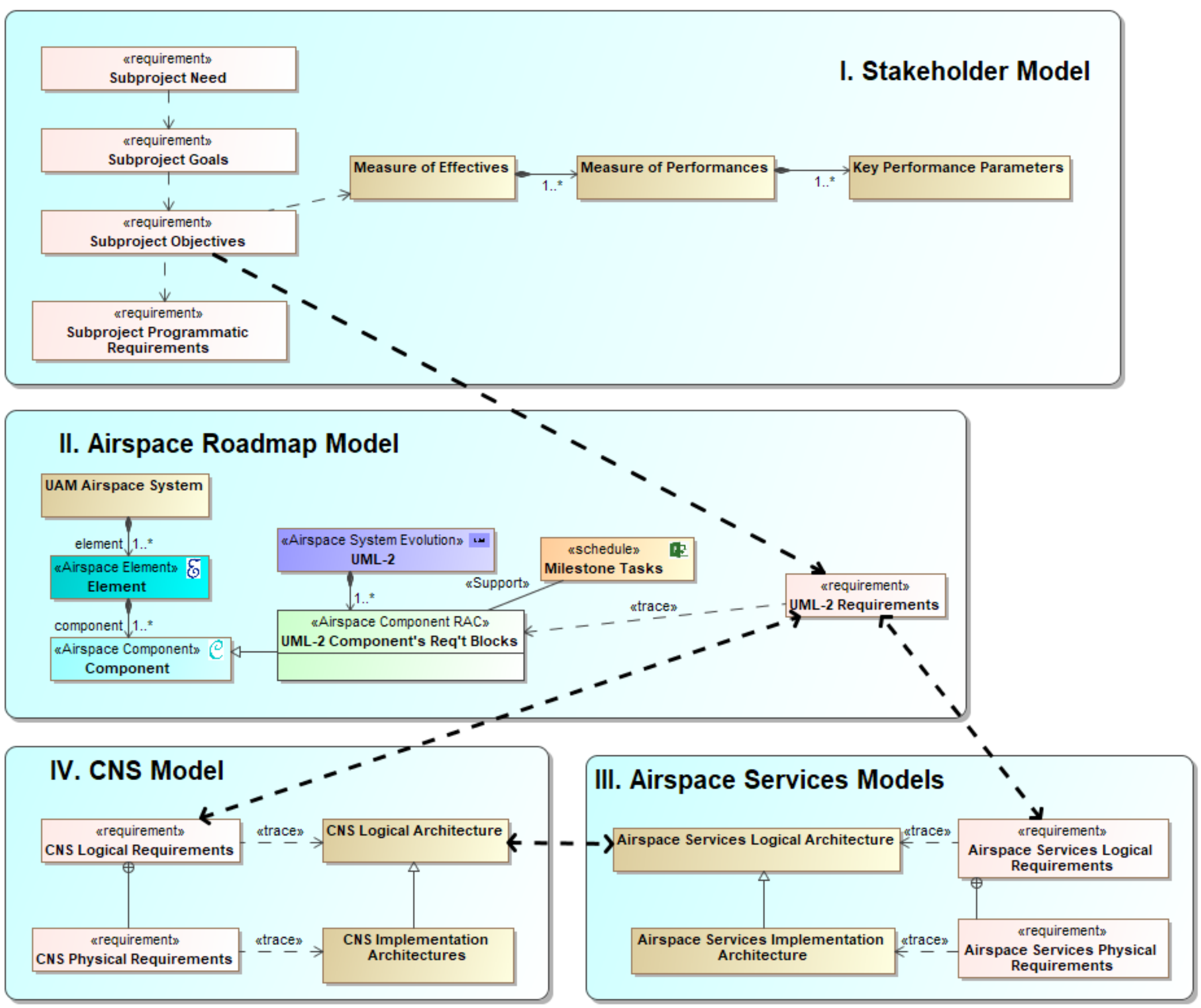

Fig. 2 Preliminary meta-model showing structure, and high-level dependencies within and between models.

A. High-level Dependencies

High-level dependencies among the four models are depicted in Figure 1 as arrows labelled as (1)-(4), and in Figure 2 as dark dash arrows. The roadmap's elements and components will satisfy the Subproject's objectives. These "satisfy" relationships are shown by dependency (1). The airspace and CNS concept development processes (through ConOps, system architecture, and system requirements) will define or refine the roadmap's requirements. These "define" or "refine" relationships, depicted by dependencies (2) and (3), will be created, revised, or deleted iteratively, and thus they are represented by bi-directional arrows. Finally, there is design inter-dependency between the airspace and CNS concept development process. This dependency, displayed by dependency (4), ensures the roadmap's requirements reflect single cohesive view of UAM concept of operations.

B. The Stakeholder Model

The Stakeholder Model (Model I in Figures 1 and 2) captures the Subproject's Need, Goals, and Objectives (NGOs), high-level programmatic requirements, Measure of Effectiveness[5] (MOE), Measure of Performance[6] (MOP), Key Performance Parameter (KPP), and traceability within the Subproject, according to the guidance from Ref. [5].

C. The Airspace Roadmap Model

The Airspace Roadmap Model (Model II) contains UAM airspace system decomposition, technical requirements, programmatic task plan, and traceability between the roadmap's technical and programmatic aspects. A thorough description of the roadmap can be found in Ref. [2]. The high-level meta-model of the UAM Airspace System (Figure 2) is composed of multiple *elements* (1-to-many), each *element* is comprised of multiple *components* (1-to-many), and each *component* has multiple "requirement blocks" that are tied to specific UMLs (1-to-many). Each "requirement block" is traced to a single requirement, as well as the milestone task(s) that it supports.

Figure 3 provides the current airspace system decomposition as defined in Ref. [2]. The airspace system is decomposed into seven research *elements.* Each research element is further decomposed into constituent *components*.

[5] Measures of Effectiveness (MOE) is the measure of success that are designed to correspond to accomplishment of the system objectives defined by the stakeholder's expectations.

[6] Measures of Performance (MOPs) defines the performance characteristics that the system should exhibit when fielded and operated in its intended environment.

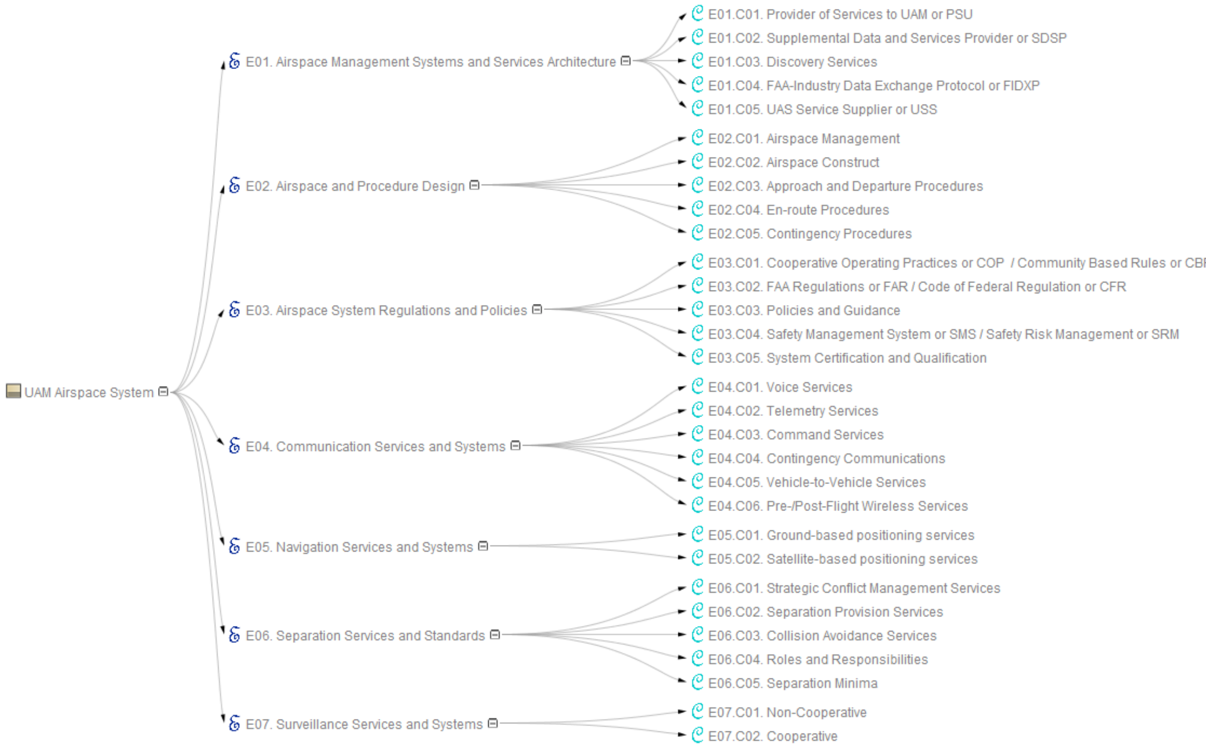

Fig. 3 Airspace system decomposition tree, generated from the SysML model with "ℰ" for research *element*, and "𝒞" for research *component*.

For each research element, a table of requirements is provided per component, and for each UML. As part of the roadmap's iteration and revision cycles, these listed requirements will be updated, added, and deleted based on NASA research and development. Figure 4 gives examples of these requirements. Each requirement is traced to a specific component within the element and for a specific UML, with a unique name (e.g., Roadmap-UML-2-R037) as a unique identifier. For example the first row in the figure, requirement Roadmap-UML-2-R037 is traced to an artifact node UML-2_RAC_E06.C01 (the 5th column). This node represents the combination of element E06, component E06.01, UML-2, and a set of its associated requirements.

#	Element	Component	UML	△ Traced To	Name	Text
1	E06. Separation Services and Standards	E06.C01. Strategic Conflict Management Services	UML-2	UML-2_RAC_E06.C01	Roadmap-UML-2-R037	The UAM Operator should use strategic scheduling services to plan operations that have minimal impact on UAM and ATM traffic
2	E06. Separation Services and Standards	E06.C02. Separation Provision Services	UML-2	UML-2_RAC_E06.C02	Roadmap-UML-2-R038	The PIC shall provide Remain Well-Clear by "see and avoid" under VFR
3	E06. Separation Services and Standards	E06.C02. Separation Provision Services	UML-2	UML-2_RAC_E06.C02	Roadmap-UML-2-R039	The PIC should provide Remain Well-Clear by "see and avoid" enhanced by automation such as advisory DAA.
4	E06. Separation Services and Standards	E06.C01. Strategic Conflict Management Services	UML-3	UML-3_RAC_E06.C01	Roadmap-UML-3-R094	The UAM Operator shall use strategic scheduling services to plan operations in accordance with established CBRs. These services should be cooperative in nature and include pre-departure scheduling, and strategic conflict detection and resolution.
5	E06. Separation Services and Standards	E06.C02. Separation Provision Services	UML-3	UML-3_RAC_E06.C02	Roadmap-UML-3-R095	The PIC should provide Remain Well-Clear from UAM, IFR, and VFR traffic by using "see and avoid" and systems and services such as assistive DAA
6	E06. Separation Services and Standards	E06.C02. Separation Provision Services	UML-3	UML-3_RAC_E06.C02	Roadmap-UML-3-R096	The UAM Operator and PIC should use assistive separation provision services in accordance with established CBRs to keep UAM vehicle away from other UAM and ATM traffic by at least the appropriate separation minima. Examples of separation provision services include DAA, and conformance monitoring by multiple human and system actors (PSU, UAM Operator, PIC).
7	E06. Separation Services and Standards	E06.C01. Strategic Conflict Management Services	UML-4	UML-4_RAC_E06.C01	Roadmap-UML-4-R134	The UAM Operator shall use strategic scheduling services to plan operations in accordance with established CBRs. These services should include pre-departure scheduling, and strategic conflict detection and resolution
8	E06. Separation Services and Standards	E06.C02. Separation Provision Services	UML-4	UML-4_RAC_E06.C02	Roadmap-UML-4-R135	The PIC should provide Remain Well-Clear from UAM, IFR, and VFR traffic by using "see and avoid" under VFR and enhanced by highly automated systems and services such as cooperative and responsible DAA.
9	E06. Separation Services and Standards	E06.C02. Separation Provision Services	UML-4	UML-4_RAC_E06.C02	Roadmap-UML-4-R136	The UAM Operator and PIC should use collaborative and responsible separation provision services in accordance with established CBRs to keep UAM vehicle away from other UAM and ATM traffic by at least the appropriate separation minima. Services will be highly automated

Fig. 4 An example of summary table, generated from the SysML model, showing examples of component's requirements by UMLs.

In addition to the technical requirements of the roadmap being modeled, critical programmatic tasks (i.e., milestone tasks) related to the roadmap are included in this model. The traceability showing the Subproject's planned tasks to the roadmap's components at each UML are also part of the same model. Figure 5 gives an example of how planned tasks are related to Roadmap elements, components, and UML. Rows are milestone deliverables by fiscal year (FY) being captured in the Subproject's integrated master schedule plan. Columns are the component-UML blocks which are artifact nodes for combinations of element, component, UML, and a set of its associated requirements. Non-blank intersecting cells present how the deliverables "support" the Roadmap's artifact nodes. Numbers shown in gray vertical bar indicate how many Roadmap's artifact nodes each deliverables support, while those in horizontal bar indicate how many deliverables each node currently has traceability. These total counts on vertical and horizontal bars help identify research gap, that is, if any Roadmap's nodes have no supporting deliverable, the Subproject can replan to address the gap. Conversely, if any deliverables do not support any node, this could be an indication of the incomplete Roadmap's *elements* or *components*.

Legend
● Support

UAM Airspace RAC

		UML-2_RAC_E06.C01	UML-2_RAC_E06.C02	UML-2_RAC_E06.C03	UML-2_RAC_E06.C04	UML-2_RAC_E06.C05	UML-3_RAC_E06.C01	UML-3_RAC_E06.C02	UML-3_RAC_E06.C03	UML-3_RAC_E06.C04	UML-3_RAC_E06.C05	UML-4_RAC_E06.C01	UML-4_RAC_E06.C02	UML-4_RAC_E06.C03	UML-4_RAC_E06.C04	UML-4_RAC_E06.C05
[10] Separation Standards		2	5	3	3	4	2	5	5	3	4	2	2	2	2	2
6: FY21: L3-Separation Assurance Concept Report	15	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
20: FY23: L3-Separation Assurance fast-time simulation results report	2					●					●					
367: FY21: L3-eVTOL flight performance models & software	3		●					●	●							
671: FY25: L1-Final report on Interactions between different Separation Services and Layer Functions to subproject	8		●	●	●	●		●	●	●	●					
932: FY23: L1-Evaluation Report on Tactical Separation Provision Services with Advisory Detect and Avoid Safety Metrics	3		●					●	●							
991: FY23: L3-Publish Collaborative Conflict Management v2.0 concept for UAM Ops (Conference paper or NASA TM)	15	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

Fig. 5 An example of traceability of planned tasks to Roadmap's elements, components, and UML.

D. The Airspace Services System Model

The Airspace Services System Model (Model III) emphasizes the ConOps from airspace services perspective at different levels of detail, which are the conceptual operations (or logical design level) and the implementable operations (or implementation design level). The logical level addresses general operational process flows,

decompositions and allocations of operational functions to actors, and general interfaces between those functions. The implementation level further provides design solutions to the logical design. Examples of the implementation level are a feasible concept solution of the nominal gate-to-gate UAM airspace operations at a specific airport for a specific mission (e.g., air-taxi, cargo, etc.) in a simulated environment, and a feasible concept solution of various contingency operations in a simulated environment. Based on these ConOps, the logical and implementation architectures as well as their corresponding hierarchical requirements can be defined, captured, and traced in the model as depicted in Figure 2. An example of the logical system actors from Ref. [6] being represented by the implementation system actors in the Subproject's design solution via a simulation study (in Ref. [7]) is displayed in Figure 6, with the columns representing the logical level while the rows presenting the implementation level and the dots displaying the representation relationship.

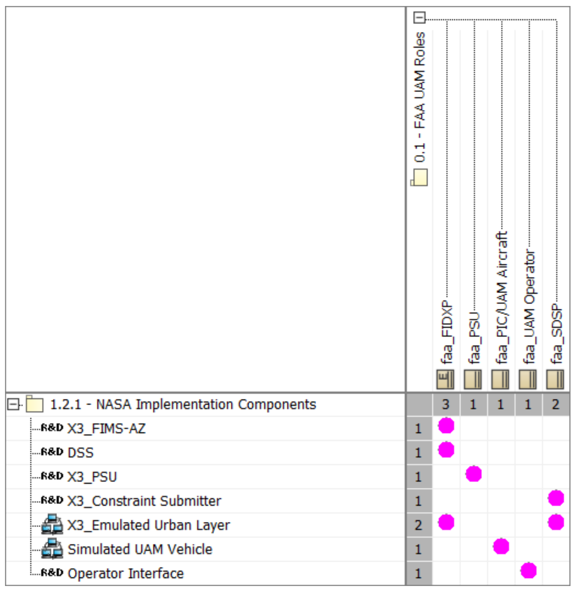

Fig. 6 An example of the logical system actors being refined by the implementation system actors.

E. The CNS Model

Lastly, the CNS Model (Model IV) captures the CNS operational concepts, systems architecture, and associated requirements. Figure 7 shows the CNS logical systems architecture, including the dataflow between sub-systems. The operational concepts cover all phases of flights and include flight operations in nominal and contingency scenarios. These operational concepts provide an event-driven view and function-to-function data flow for the CNS system. The systems architecture details a hierarchical breakdown from a high-level down to individual software subsystems, which carry data to internal and external system elements during flight operations. The CNS requirements are refined through the development of the operational concepts and system design and are consequently mapped to satisfying system elements as the CNS analysis matures.

Facilitated by the systems architecture, the CNS analysis has been done to perform necessary simulations to better understand development decisions and concerns such as network loading, interference, frequency usage, and antenna placement. The data necessary to perform simulations is captured (Figure 8) and adjusted through the systems elements in the model, which allows the modeling team to work closely with the modeling and simulation team while scenarios are tested.

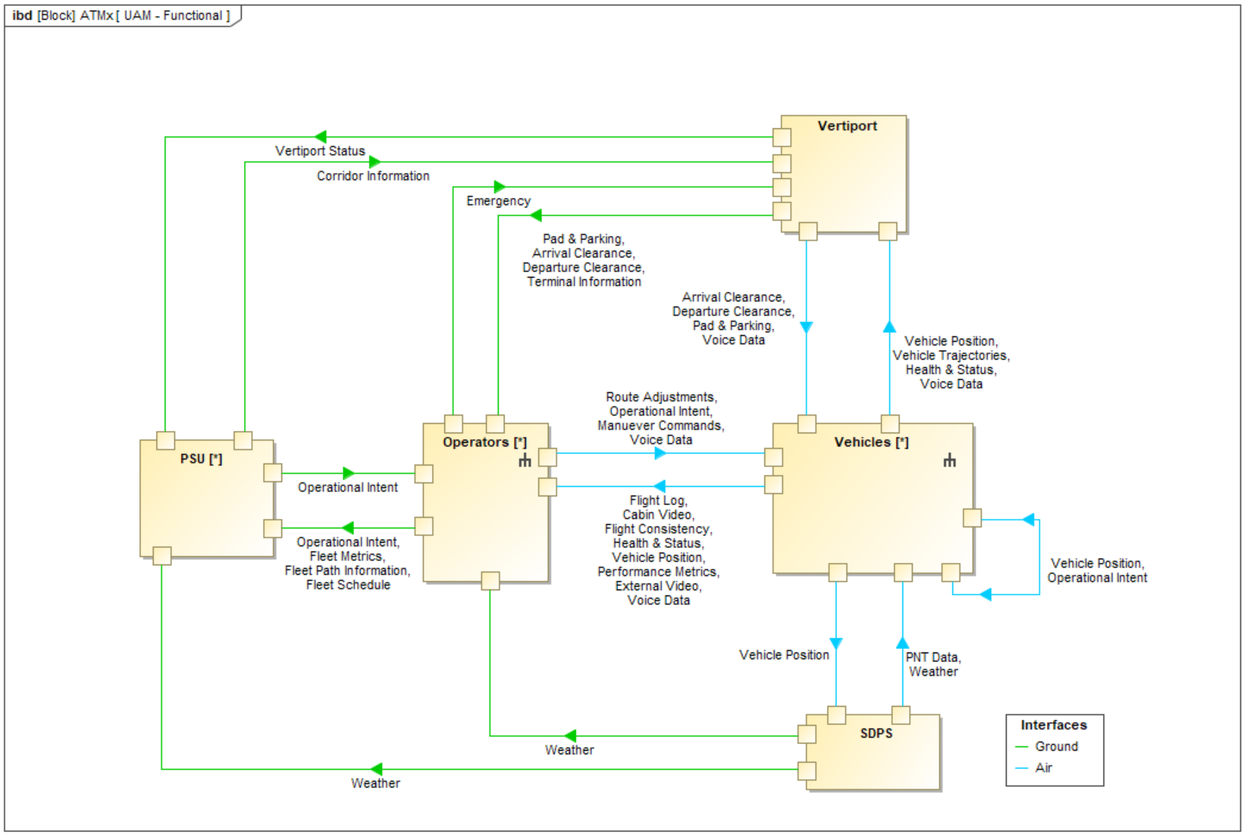

Fig. 7 CNS logical architecture with detailed dataflows

#	Name	Documentation	MsgID	MsgType	MsgSize	M	N	Flee		MsgSrc	MsgDes	MsgPriority
1	Aerodrome Airspace Loading	Loading analysis for the aerodrome airspace	AAL	Triggered	400	1	TCP			A	PSU	Normal
2	Aerodrome Master Schedule	Full schedule for operations at Aerodrome. Includes all outbound and inbound flights scheduled as well as downtime for maintenance	AMS	Triggered	250	1	TCP			A	FM, PSU	Normal
3	Arrival Clearance	Clearance for aircraft to land at source Aerodrome	ACL	Triggered	95	1	TCP	100	1	ATC-A	AC, PIC	High
4	Cabin Video											
5	Corridor Information	Flight track details for fleet moving to and from aerodrome. Route tracks	FPI	Triggered	100	1	TCP			FM	A	Normal
6	Customer Information		C	Triggered	50	1	TCP			C		Normal
7	Customer Service Request	Customer request for flight services.	CSR	Triggered	50	1	TCP			C	FM	Normal
8	Departure Clearance	Clearance for aircraft to depart from source Aerodrome	DCL	Triggered	100	1	TCP	100	1	ATC-A	AC, PIC	High
9	Detect & Avoid	Proximity warning data, automatic maneuvering. Can be Peer to Peer	DAA	Triggered	500	1	TCP	20	1	AC	AC, FM	High
10	Emergency	Urgent request from aircraft. Mechanical failure or other anomalous situation	EM	Triggered	100	1	TCP	1	1	PIC	ATC-A, FM,	Critical
11	External Video											
12	Fleet Metrics	General fleet information. Number of aircraft, type, charge capacity, efficieny, FAA documentation	FM	Triggered	200	1	TCP			FM	PSU	Normal
13	Fleet Path Information	Flight track details for fleet moving to and from aerodrome. Route tracks	FPI	Triggered	100	1	TCP			FM	A	Normal
14	Fleet Schedule	Full fleet schedule. All flights, to and from all destinations.	FS	Triggered	600	1	TCP			FM	FM	Normal
15	Flight Consistency	Position reports, waypoints, etc	FC	Periodic	500	1	TCP	100	10	AC	ATC-A, PSU	High
16	Flight Log	Passenger departure manifest, flight service performance, vehicle status, flight times, pad and parking information, pilot and uam operator sign	PFR	Triggered	100	1	TCP	100	1	AC, PIC	FM, AO	High
17	Health & Status	Automatically reported data about the vehicle. Performance data, battery life, mantainence thresholds, general diagnostics	H&P	Periodic	700	1	TCP	100	10	AC	FM	High
18	Manuever Commands											
19	Operational Intent	All information necessary for service. Waypoints, source, destination, clearances, payload, passenger manifest, timing, landing zones	FP	Triggered	1000	1	TCP	100	1	FM	AC, PSU	High
20	Operations Request	Request from UAM operator to service an airspace area	OR	Triggered	50	1	TCP			FM	A	Normal
21	Operator Activity Detail	Description of new operator activity for planning and scheduling team to take into account when scheduling services	OAD	Triggered	100	1	TCP			A	A	Normal
		Specific area of service for UAM operator in given										

Fig. 8 An example of CNS logical data attributes

IV. Planned Activities

As the UAM Airspace research & development lifecycle progresses, all models will be iteratively evolved in a coordinated manner. It is expected that the Stakeholder Model will be updated on an annual basis, posing the least frequent revision, among other models because those requirements are at the programmatic level. Planned activities specifically for the Airspace Roadmap Model include:

- addition of the roadmap's elements or components,
- definition or refinement of the component's requirements,
- refinement of requirement's ontology definitions (i.e., requirements with "shall/should/will" statements) and their practical interpretations or implications for the airspace's community at large, and
- characterization of validation scales (i.e., requirements being verified and validated through flight tests versus through simulation studies will likely have different maturity scales).

Additionally, as the inter-dependencies among models are being captured, they will be statistically analyzed to monitor, gain insight, predict, and plan future research works toward meeting the Subproject's goal. When tasks are identified to advance the research towards the goal of UML-4, traceability to the Roadmap is identified a priori. Individual research activities will generally impact multiple research elements and components, usually focused on a particular UML. This helps to scope and focus the research activity, as well as provide foresight into how the total body of knowledge will evolve upon successful completion of the research activity.

When a research activity is completed, it generally yields a deliverable and a set of associated research requirements. The notional figure below (Figure 9) illustrates how recent deliverables by the Subproject are traced into the research roadmap. The dark blue represents the number of the requirements identified to-date, as provided by the deliverables. The blank rows indicate the components that are not part of the Subproject's planned tasks but are included in the Roadmap to emphasize their dependencies with the Subproject's responsible components.

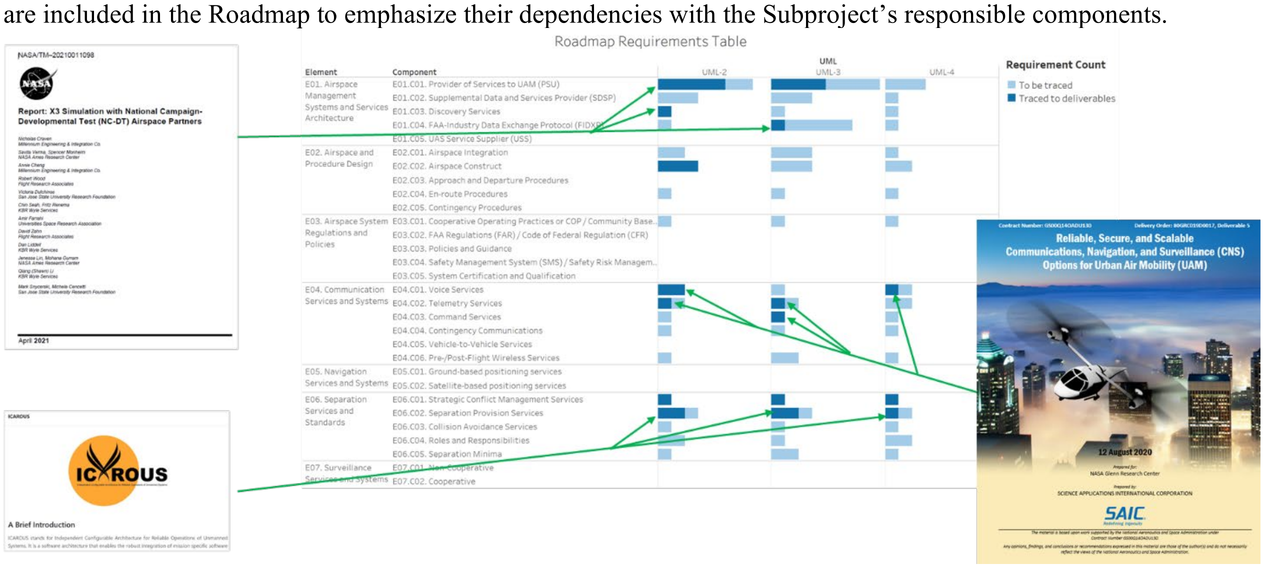

Fig. 9 Deliverable tracing to the Roadmap

A completed plan to track research progression of the UAM airspace towards UML-4 is given in a complementary paper Ref. [8]. The reader is directed to Ref. [8] for a thorough description of visualization dashboard to track the Roadmap's progression. Partial discussion related to this paper is given here. All Subproject's milestone deliverables are traced into the Roadmap. At the time of this writing, the Subproject has planned milestones up to fiscal year 2025 (FY25) and has expected to have research work reached about half of the goal of *evolving the UAM airspace towards UML-4*. Preliminary research progression dashboard at the end of FY21, FY23, and FY25 is shown in Figures 10, 11, and 12, respectively, with only components the Subproject is responsible for being displayed. In addition, similar dashboards at the end of FY22 and FY24 are available, but not shown in this paper.

The "Completed work" as described previously in Figure 9 is shown (dark blue) here as the percent of the Subproject contribution toward the goal (the CC Goal line in the figures). The TC1 Goal line indicates the expected research work accomplished by the end of FY25 reflecting the UAM airspace at UML-3. At the end of FY21, all planned milestones to the end of FY25 are shown in Figure 10 as "Planned work" (dark gray). At the end of FY23, the cumulative planned milestone deliverables up to the end of FY23 are projected to be completed and are shown as

"Projected completed work" in Figure 11. At the end of FY25, all "Planned work" (dark gray) in FY21 will become the "Projected completed work" (Figure 12).

Future research (light gray) in all three figures are the remaining percent of the Subproject work to evolve the UAM airspace to UML-4 and are constant across all figures. The "Completed work" in all three figures are also constant because it represents the cumulative completed work to-date, but it will grow for the outyears when more deliverables are completed. Finally, it should be reiterated that this visualization is a living dashboard which will be updated and revised whenever there is any change such as the roadmap decomposition, the planned task (milestone) list, or milestone completion events.

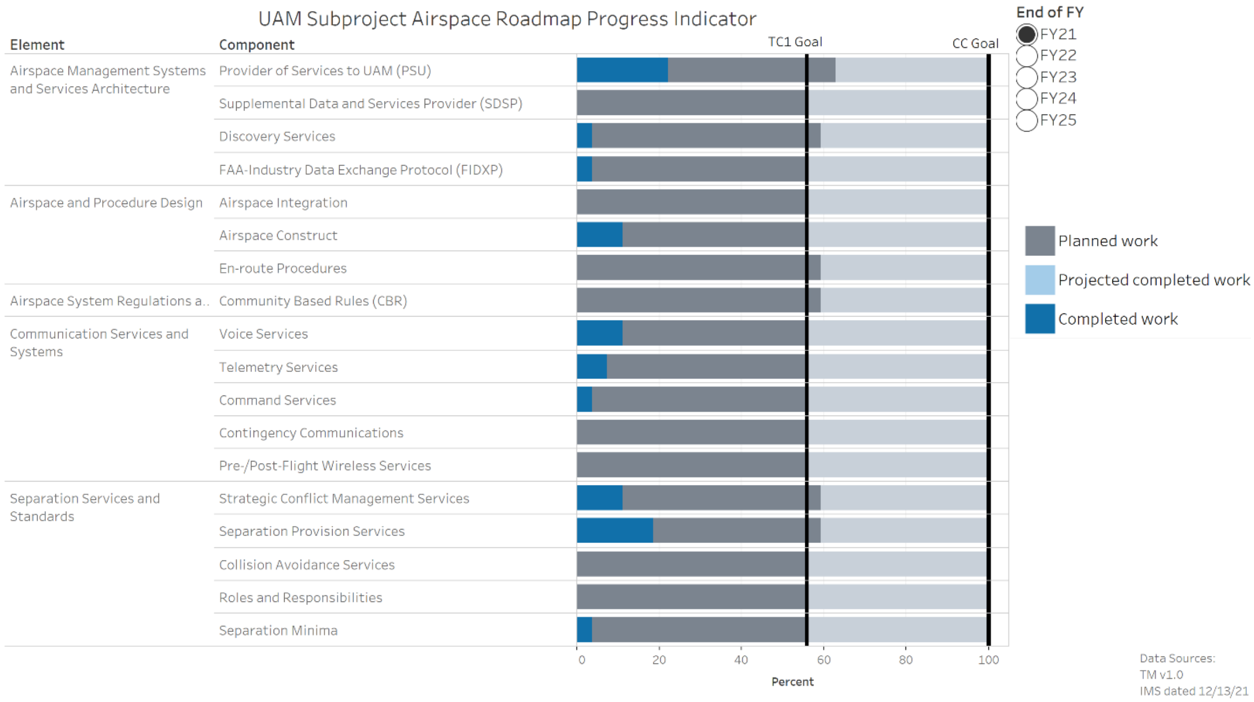

Fig. 10 Preliminary Roadmap progression dashboard for FY21

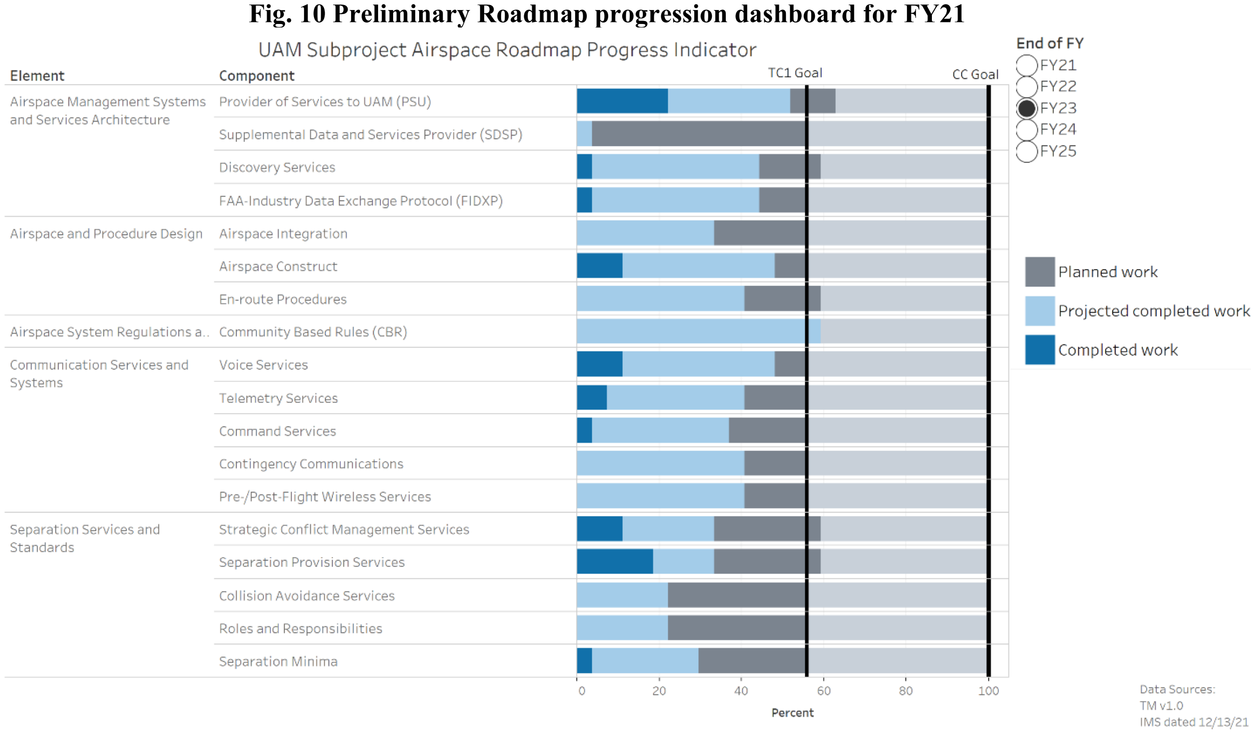

Fig. 11 Preliminary Roadmap progression dashboard for FY23

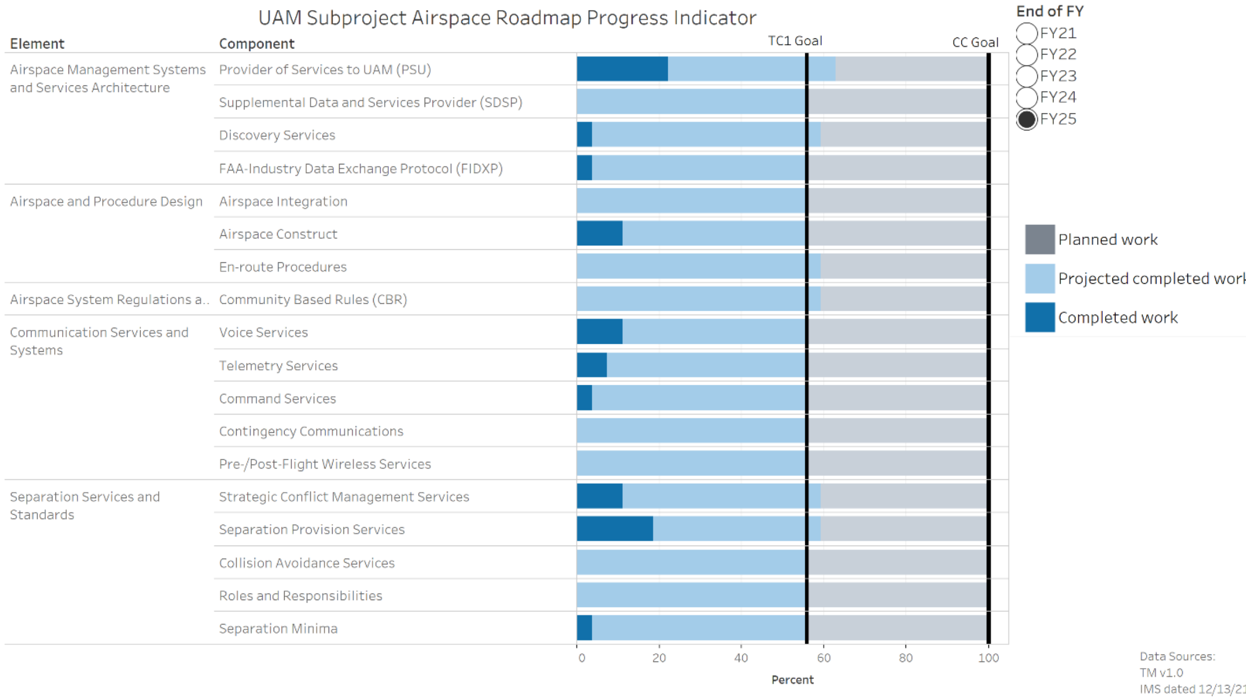

Fig. 12 Preliminary Roadmap progression dashboard for FY25

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